ARMY RESEARCH LABORATORY

An Examination of the Nature, Effects, and Control of Electromagnetic Fields

by W. J. Sargeant, C. Marinos,
and A. Zielinski

ARL-TR-2232 May 2000

Abstract

Electromagnetic (EM) armaments and electric launchers are emerging systems that are of increasing importance to the armed forces. Included in this category are the railgun, coilgun, reconnection gun, electrothermal (ET) gun, and electrothermal-chemical gun (ETC). The system design issues for managing EM fields generated by these devices and their associated pulsed power systems, which may include compulsators and pulse disk alternators, in the military applications for which they are intended have been the subject of this study.

Acknowledgments

This work was supported by the Program Manager for the Army's Electric Gun Program, Dr. Ed Schmidt, U.S. Army Research Laboratory (ARL). Also, useful comments and discussions were contributed by Mr. Harry Moore, U.S. Army Armament Research, Development, and Engineering Center (ARDEC), Dr. Ian McNab and Mr. Cliff Thomas, The Institute for Advanced Technology (IAT), and Mr. Bruce Benwell (ARL).

INTENTIONALLY LEFT BLANK.

Table of Contents

List of Figures

INTENTIONALLY LEFT BLANK.

1. Background

The nature and effects of the resulting electromagnetic (EM) fields that would be generated by EM or electrothermal-chemical (ETC) platforms and systems are not well understood—in particular, EM fields associated with pulsed-power generation and storage, switching, buswork, control systems, and the launcher itself, as well as their impact upon personnel, equipment, and related subsystems.

Experience has shown that electromagnetic interference (EMI) and electromagnetic compatibility (EMC) shielding for purposes of equipment operation depend on the specifics of the design. This portion of the assessment should be undertaken when a specific electric armaments system is designed. However, to initiate the process, this report addresses the feasibility of achieving adequate shielding to meet personnel, structural, and electrical performance and recommended design practices. The initial approach was to identify critical issues regarding EM radiation signature. The following questions were raised:

(1) Can sufficient shielding be incorporated into practical armament designs so that EMI/EMC field levels can be reduced to meet those described in "best practice" guidance available today?

(2) How should shielding effectiveness as a function of system efficiency, volume, and mass trade-offs as an engineering design issue be addressed?

(3) Is there conclusive evidence that is indicative of the existence of adverse biological effects on humans (both thermal and nonthermal) resulting from exposure to pulsed EM fields?

(4) To what extent might shielding for a monopulse field source give rise to guided surface waves, requiring further damping?

The study considered, to first order, interactions with equipment and procedures already established as a part of the fire-doctrine (weapon, single-shot, etc.) and component behavior.

2. Introduction

EM armaments and electric launchers are emerging systems that are of increasing importance to the armed forces. Included in this category are the railgun, coilgun, EM armor, electrothermal (ET) gun, and the ETC gun. The subject of this study is the system design issues for managing EM fields generated by these devices and their associated pulsed power systems, which may include compulsators [1], pulse disk alternators [2], and capacitor-based pulsed power sources with an emphasis on military applications [3].

Electric armaments require pulse power systems (PPS's) that can generate large peak powers and, in the special case for railguns, that can generate rail currents in the mega-ampere range. During the armature acceleration process, arcing may also occur, leading to the generation of additional transient high-frequency EM fields. Switching systems can also be powerful generators of very high-frequency (VHF) transient EM fields.

Railguns generate EM fields whose dominant energy spectrum frequency components lay between DC and tens of kilohertz. These fields may not only be a concern for the traditional problems of EMI/EMC, but also may be of concern to biological systems. Over the last decade, there has been steadily increasing attention at both national and international levels as to the potential effects of EM fields in this frequency range on biological systems [4–21]. Although many studies have described biological effects that may be related to EM field exposure, these effects have not occurred consistently and cannot always be replicated by other laboratories.

3. Observations Arising From Research on the Existing Literature and Databases

Here the intent is to ascertain the nature of pulsed EM fields and their shielding in the context of single-pulse environments. It may well be that the time derivative of the magnetic induction field will be the system EMI/EMC driver—even for personnel safety because the impedances are very low in these systems [25].

In this work, reference is to the biological regulatory standards of the American Conference of Governmental Industrial Hygienists (ACGIH) instead of citing additional regulatory guidelines provided by other entities. There are many reasons why it is sensible to accept one set of guidelines (ACGIH's) as the sole source of "recommended practice" for this study [29]. These reasons are:

(1) It would alleviate possible confusion and contention between existing standards.
(2) The U.S. Army officially endorses it.
(3) The limits are easy to understand and check.
(4) It appears to be widely accepted in industrial and occupational settings.

3.1 Existing Literature and Databases. The major components that the electric armament system comprises are a pulsed alternator, here taken for example as the compulsator [1, 30], the switching system, and interconnection(s) to the breech of the EM launcher. In the following subsections, initial discussions are concerned with magnetic fields primarily from the compulsator, both to illustrate how they can be shielded to be in compliance with currently desired recommended practice, as well as to relate the feasibility of the shielding effectiveness to both low and high field situations [31–33]. It should be noted, however, that electric fields can also force EMI/EMC requirements. The electric fields in an electric armament system are of relatively lesser concern because of the low discharge impedance. Nonetheless, they are addressed in a subsequent section.

3.2 Magnetic Fields

Compulsator Magnetic Fields. For the multimegajoule class of compulsator, this discussion provides an estimate of the magnetic flux density environment (adapted from [34]).

This class of generator has a field coil located on the rotor that produces a rotating excitation magnetic field. Since the generators of this class are air core (i.e., there is no ferromagnetic structure to channel the flux), the magnetic field is free to permeate through the surrounding environment. The magnetic field strength decays according to equation (1), in the absence of any shielding [25]:

$$B_r = B_O \left(\frac{r_{fa}}{R} \right)^{p+1} . \tag{1}$$

Here, B_O is the field strength at the average radius of the field coil (r_{fa}) and R is the radius of interest such that $R > r_{fa}$ and p is the number of pole pairs in the compulsator. The environmental field decays as the distance from the source (e.g., field coil) is increased. The rate of decay is faster for a many-pole machine than for a two-pole machine.

- **Eddy Current Shielding.** There are two tradeoffs that can be studied with regard to the shielding. These are the number of poles in the machine and the proximity of the environmental shield to the machine. With the shield, more excitation (i.e., ampere-turns) is needed to establish a given field strength near the armature winding as the number of poles increases. This may argue for a lower number of poles. However, as the number of poles increases, the field strength decays more rapidly and shielding will become easier at reasonable distances from the machine [25].

In order to minimize adverse effects against electrical components (e.g., current collection systems) and personnel, it may be necessary to provide shielding at some outer radius of the machine so that the magnetic fields outside this radius are inconsequential. This shield could take the form of an aluminum cylinder that runs at least the entire length of the machine and is a few skin depths

thick at the electrical frequency of the machine. At 600 Hz, this thickness could be as little as 7 mm (0.275 in.). An alternative scheme would use the walls of the vehicle itself as the shield. Measures to separate the machine from personnel and equipment may be necessary so that the walls do not adversely distort the magnetic field distribution within the machine.

It must be remembered that the conducting shield, so chosen because of its low density and large electrical conductivity, performs its task due to induced eddy currents on the inner surface of the shield. These eddy currents annul the fields produced by the field coil, thus reducing or eliminating the external fields. In so doing, the fields internal to the machine are also reduced. The field coil ampere-turns must therefore be increased to maintain the same radial field strength near the armature winding [25]. This effect will, of course, be enhanced the closer the shield is placed to the machine. Shield placement, depending on specific machine design, will affect overall efficiency. As part of the system trade-off during the design portion, there is thus a minimum distance for the location of the shield that is different for a machine with different poles [25, 30, 34]. At the system level, environmental shielding will have minimum impact on system efficiency for high-efficiency alternator designs [25, 27].

For the worst case considered for the exit criteria machine (ECM), the use of an aluminum cylinder shield would reduce the field just outside the shield to on the order of $(1/e)^2$ of the 2.5-T flux density from the outer field coil, or to about 0.3 T (3,000 G). The location of the aluminum shield can be determined from EM analysis of the generator/shield system. However, for this first-order examination, the peak flux density generated within the machine was used at the surface of the aluminum shield (i.e., no accounting for the field decay as indicated by equation [1]). The peak flux density after the aluminum shield then represents the starting point for further shielding of the ECM for a given total system environment.

Composite (i.e., multilayered, conducting, and hard magnetic materials) shields could also be used to optimize the thickness. In a composite shield, the first layer is a good conductor such as aluminum, which attenuates the field to be below the level of saturation of magnetic hard materials,

and the second layer would be made of magnetic hard or semi-hard materials (e.g., the vehicle walls) [25].

• **EM Launcher Magnetic Fields.** Work in this area is recommended as a part of a continuing activity, as this report concentrates on determining if the pulsed alternator (here, for example, a compulsator) portion of the complete system could be shielded to meet "best practice" guidelines. With that demonstrated, the issue here is that the EM launcher and rail magnetic fields can now receive the further analytical and experimental understanding necessary to meet "best practice" in this physical area. Some experiments have been conducted with regards to shielding effectiveness and railgun performance [35]. An environmental shield placed just outside the launcher containment structure appears to be sufficient to manage the environment without affecting performance [35].

• **Busswork and Interconnect Magnetic Fields.** In order to achieve a high system efficiency, it may be necessary to develop high-power, shielded cables. The shielding approach described previously applies to this issue area, although cabling systems require mechanical flexibility. A flexible coaxial cable has been developed and is capable of conducting up to 500 kA for a few milliseconds [36]. Theoretically, a coaxial cable produces zero external magnetic field. However, in practice, some field escapes. Additional shielding can be incorporated easily [36].

3.3 Electric Fields. The significant area of concern resides in monopulse field generation, namely in regions between the output of the high energy switching and the gun system [37]. This regime is a result of rectifying the alternator current to the gun. Time constraints have not permitted adequate analyses of any guided wave issues at the present; however, this issue of guided surface waves has been addressed in a significant paper presented at the 1994 Progress in Electromagnetics Research Symposium held in The Netherlands [38]. In this report, the propagation of a microwave monopulse from a point source into layered media was modeled analytically and studied experimentally. The wave propagation along the layers was validated experimentally against the model predictions. It was observed that if the layer thickness is close to the so-called "localization

length," the monopulse is highly attenuated and the rise-time is lengthened somewhat, with an additional long exponential decay. This work concluded that:

(1) The exponential decay is shape-independent of any monopulse details.

(2) All the previous fields are new discoveries in the context of this class of media.

This means that problematic surface waves could exist near nonconducting substrates. Such waves, although low in intensity, could couple out at reflective end points to structures and lead to distinctive EM signatures and EMI in unwanted areas.

4. Field Mitigation

4.1 Passive

Magnetic Shields (After [22]). Shields for small-magnitude, unidirectional, and low-frequency magnetic fields are made of magnetic material, preferably having a high initial permeability. Such shields act as low reluctance paths for the flux, thereby diverting the flux away from the space to be shielded.

The most important practical use of magnetic shields in power systems is to minimize voltages induced in transformers by magnetic fields at power frequencies. This is accomplished by placing the transformer in a magnetic shield normally consisting of a rectangular box or a short cylinder with closed ends. The degree of protection obtained in this way depends upon the size and thickness of the shield, and upon whether the shield consists of a single layer of magnetic material or several concentric layers separated by air spaces. In the case of a single layer shield, the effectiveness is approximately [23]:

$$\frac{\textit{Magnetic field in absence of shielding}}{\textit{Magnetic field with shielding}} = 0.22\,\mu\left[1-\left(\frac{t}{r_0}\right)^3\right], \tag{2}$$

where

μ = initial permeability of shield,

r_0 = radius of sphere enclosing the same volume as defined by the outer surface of the shield, and

t = thickness of shield ($< r_0$).

Equation (2) is based on assuming that the shield is infinitely long (i.e., no end effects) and the source is a steady, uniform field (an alternating field is acceptable provided an "effective value" for the permeability is used). The maximum possible shielding factor obtainable is 0.22 μ. Approximately 50% of this value is realized when the thickness of the shield is 1/5 of the radius of the equivalent sphere; relatively thick single-layer shields are accordingly uneconomic [22]. Additionally, for a Permalloy shield (μ = 5,000), the theoretical maximum attenuation is 60 db and is attained for relatively thick shields.

When the degree of shielding required is greater than 50 db, it is not only advantageous but necessary to utilize multiple shells, as shown in Figure 1. Equation (2) correlates to the curve labeled "A" and indicates relatively little gain in attenuation is obtained for thick shields (ratio of the outer radius to the inner radius > 1.1).

The effectiveness of magnetic shields depends primarily upon the initial material permeability and is roughly proportional to μ^n, where n is the number of concentric layers. Permalloy and similar magnetic materials having high initial permeability are, accordingly, vastly superior to ordinary cast iron or silicon steel, particularly in the case of multilayer shields.

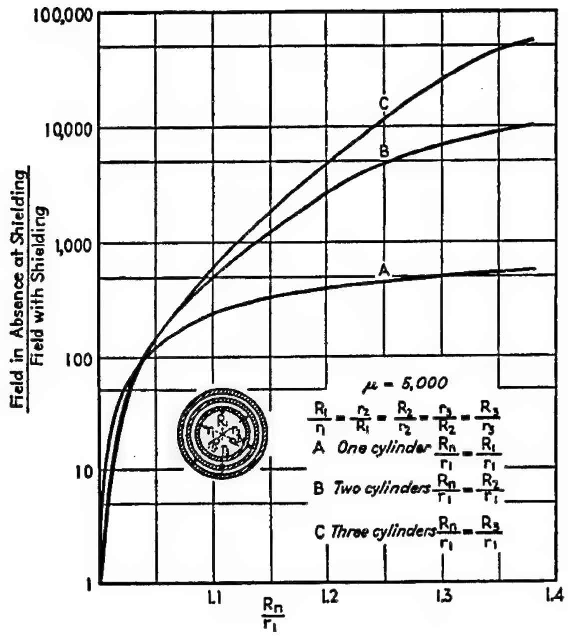

Figure 1. Performance of Concentric Cylindrical Magnetic Shields [22].

A magnetic shield enclosing an air-core coil causes the inductance to increase as a result of lowered reluctance offered to the flux paths by the high permeability material. The effective resistance of the shielded coil is also increased because of eddy current and hysteresis losses in the magnetic material. Engineering design determines whether these losses are acceptable.

Figure 2 shows curves illustrating the shielding effectiveness of various typical shielding composite structures for low-frequency (<< 1 MHz) fields [22, 39, 40]. Note that with configuration C and an additional layer of Permalloy, more than 100 db of shielding effectiveness should be achieved at 600 Hz. Operating Permalloy at up to 0.4 T (4,000 G) remains below its B_{sat} of 0.5–0.6 T (5,000–6,000 G) [22]. With such a level of additional attenuation applied to the ECM, the magnetic field signature would be reduce from the 0.3 T just outside the aluminum shield to less than 3 μT (30 mG), well in compliance with current recommended exposure limit of 100 μT at 600 Hz [29]. Using configuration C data [24], the total Permalloy shield thickness is roughly 10 mm, which is suitable for volume-limited applications. For weight-constrained systems, aluminum may suffice, owing to its smaller density (2,700 kg/m^3 vs. 8,600 kg/m^3). For a shield without closed ends, the attenuation can be expected to be reduced by about 15 db [24].

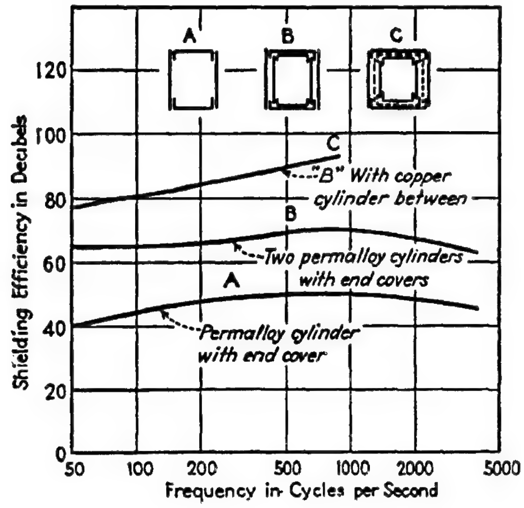

Figure 2. Curves Showing Effectiveness of Various Typical Shielding Arrangements [22].

Further attenuation (5–10 db) could be accommodated at these low field levels (i.e., at B_{max} less than 1 mT) through an additional TI-Shield layer of shielding. It should be noted that the effectiveness of magnetic shielding—for example, the TI-Shield of copper/Permalloy layers—can become degraded in the forming, soldering, cutting, and other assembly phases, requiring considerable care in shield fabrication [26, 41].

Figure 3 shows the representative near-field 50/60-Hz magnetic fields arising from typical consumer power electronics [21]. For a given appliance, the field decays roughly as the inverse of the distance. Also, for the same type of appliance, but different manufacturers, the field can be significantly different, owing to the design, construction, and operation of the appliances. These data are plotted as high and low exposures and range from ~1 μT (10 mG) to 10,000 μT (100 G) over a 1-m distance. For reference, three selected field generators (e.g., appliances) are also indicated on the plot with large circles, and represent the smallest variability amongst all the appliances.

The conclusion is that proper engineering design considerations are expected to allow reduction of the environmental magnetic fields from the ECM to be reduced to less than 3 μT, equivalent to the exposure on a Washington, DC, subway ride.

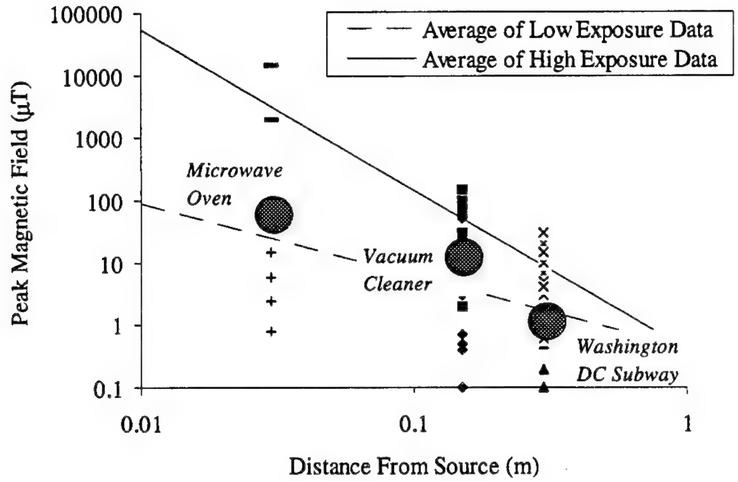

Figure 3. Measured Peak Magnetic Fields Produced by Numerous Consumer Products (Adapted From [21]).

4.2 Active Shielding. Active shielding utilizes sensors, feedback, and field generators that serve to cancel the fields generated by the operational electrically energized system [25, 26]. In the case of EML systems, such active attenuation may be needed for rail and muzzle fields insofar at they radiate into the battlespace outside of the mobile platform on which the EM system is installed. Such active attenuation is highly system dependent so that it would make practical sense to address this approach once it is determined to be necessary for shielding in these areas and after second-tier-level designs at the system level have been completed. Needless to say, large, confined magnetic fields are best attenuated with active shielding to maximize the overall system efficiency.

5. Exposure Limits

The ACGIH threshold limit value (TLV) for magnetic flux density for routine occupational exposures is 1 mT (10 G) for a full work-shift, at the power frequency of 60 Hz. The International Non-Ionizing Radiation Committee of the International Radiation Protection Association (INIRC/IRPA) has set exposure limits for magnetic fields at 0.5 mT (5 G) for a whole working day and short-term exposure (not to exceed 2 hours) of 5 mT (50 G). These guidelines, however, do not address the carcinogenic potential of extremely low frequency (ELF) magnetic fields, owing to the

lack of any definitive experimental data [14]. Also, the interference of magnetic fields with implanted cardiac pacemakers is not addressed. Pacemaker malfunction depends strongly on the manufacturer and type (e.g., unipolar or bipolar). However, almost all pacemakers are influenced at a field strength of 250 μT [15], which is half the recommended 500 μT for a whole working day exposure.

All anticipated personal exposure results in this study were below the guidelines for ELF electric and magnetic fields established by the ACGIH and the INIRC/IRPA.

The engineering projections of the magnetic fields on the exterior side of shielding recommended for the ECM result in values that meet the ACGIH TLV and should be experimentally validated. The most recent ACGIH handbook on TLVs [29] has for 600-Hz operation the equation for determining compliance:

$$B_{TLV} = 0.06/f, \tag{3}$$

where f is the frequency in hertz and B_{TLV} is the threshold acceptable value for the magnetic field over the exposure period (8-hour work-shift). At 600 Hz, B_{TLV} is then 0.1 mT (1 mG). It is noted that a change is "intended" to be made that will restrict equation (3) to the frequency range of 1 to 300 Hz. Since it is wise to "look ahead," the intended change is used in this study and reads:

"For frequencies in the range of 300 Hz to 30 kHz occupational exposures should not exceed 0.2 mT."

By utilizing the intended change, the magnetic field exposure may be twice as high as previously calculated, and the required shielding will be roughly 60 db, which can be provided by multiple layers of TI-Shield, yielding more EM attenuation than ACGIH standards require.

The ECM, with appropriate shielding as described above, will have significantly less magnetic radiation than this "recommended practice" level.

5.1 Mechanism(s) for Cellular Disruption. A causal relationship between EM fields, in the frequency and field intensity ranges that are characteristic of railguns, and observed deleterious effects on biological systems has not been established [21]. Moreover, there is a paucity of scientific data upon which detailed analysis could be undertaken. The few solid scientific studies that have been done do not technically support the contention of adverse affects (e.g., odds ratio ~ 1.2) resulting from typical, and even in some cases involving unreasonably high, field levels [21]. In-vitro studies (i.e., cells) indicate no reproducible genotoxicity for any field strength, although a variety of changes in the cellular signal-transduction process is noted for magnetic fields greater than 100 μT. The mechanism of transferring damage to cells and tissue has to be considered. These issues are frequency and magnitude dependent. Despite the realities of the situation, the only responsible approach is to proceed with the development of a weapon system, paying attention to potential biological effects resulting from exposure to EM fields [42].

The possibility that EM fields associated with electric power transmission may cause medical conditions cannot be dismissed. However, the inconsistency between published studies and the lack of plausible biological explanation for such an association means that a causal relationship has not been established.

Electric armaments also have the capability to generate large currents. These currents could be topologically significant since cells are not homogeneous. Local thermal stress could occur as well as forces on fluids conducting these induced currents. This matter is recommended for further study by bioengineers who are expert in this area [21].

- **Transient Field Exposure.** Transient field data and their effects are extremely rare, due in part to the lack of standards to define transients and the abundance of continuous alternating current (AC) electric power. One area of interest in the assessment of epidemiological exposure is the measurement of magnetic field characteristics. Alternative exposure metrics, other than average field intensity, could be related to health effects [43, 44]. In some cases, biological effects on

embryo development seemed also to depend on the shape or waveform of the EM field, specifically the pulse rise time and time rate of change in the magnetic field [45, 46]. In another study, EM fields were observed to produce responses in lymphocytes that were enhanced, while inhibited in others. The extreme dependence of the results on the physical characteristics of the field has been noted in the literature [47]. Finally, physiological studies also indicate an unusual dose-response relationship for a transient environment [48]. A peak magnetic field (100 μT, 1,000 mG) with a 5-ms rise time, applied for 1 s and turned off for 1 s, reduced hormone concentrations for exposures less than 60 minutes. However, these effects were not seen in exposures lasting for 60 minutes.

5.2 Equipment. Little data have been found to date on EMI sensitivity of electronics to this class of fields [26]. If the shielding level recommended in the "best practice" areas is utilized, it is unlikely that electrical equipment interference will be observed. To validate this assumption is rather complex and requires an architectural analysis similar to that undertaken for modern military airplanes and mobility platforms [31, 32]. At this time, such an analysis is recommended.

6. Environment

6.1 General Approach. Electric gun systems range from ground mobile platforms to large facilities, but the primary features are similar. A major contribution to the EM environment is due to the PPS, which contains the energy storage and pulse-forming network. Electrified armaments all have similar PPS's. The fields due to a PPS can be determined in a straightforward, although not necessarily simple, way from the circuit details and shielding that typically isolate a PPS from its surroundings. To a large extent, the fields produced by a PPS will scale as the current, notwithstanding frequency spectrum anomalies produced by the nonlinear switching elements [37]. Because of the large amount of detail that a PPS comprises, it is recommended that theoretical estimates of the generated fields by a PPS be supported by an ample experimental base.

For railguns, there is a robust and unique component of the magnetic field produced by the current that flows in the rails. Magnetic fields generated by a laboratory model of a railgun have been predicted and experimentally verified [49–53]. The peak fields and frequency content will

readily scale to actual system dimensions. These initial results permit taking the next step with high engineering confidence, which includes the prediction of the environment that is modified by shielding.

6.1.1 EMI/EMC Issues. Research has been conducted into both simple and series augmented railguns. These two types of electric guns produce similar EM environments where design features such as armature package and rail containment introduce relatively small changes in the temporal behavior and peak intensity of the fields at a few bore distances from the same current. The amplitude of the fields can be scaled to operational size systems.

The principal contribution from ET/ETC guns will come from the PPS, which is typically enclosed in a robust physical container that is concurrently shielded. For example, the design features of the PPS may include safety cages over capacitors, installation in a mobile system (e.g., the Army's 9-MJ pulse power module [PPM]), or a metal structure to safely contain rotating machinery.

Features unique to systems such as those described must be taken into account in a detailed suite of EM field calculations. Because of the complex structure of the PPS, it is probably best to rely on field experiments in order to evaluate the environment. Theoretical calculations are quite valuable, however, for providing guidance to the experimental design. For ETC gun and tube propulsion, the electrical energies per pulse range from one to two orders or more smaller than for EML systems. The same methodology as described in this report can similarly be applied, albeit the maximum magnetic fields will be significantly smaller.

Military systems are designed and constructed so that the electronic components are compatible during normal operation, and the entire system is not itself a source of unwanted EM interference to other friendly forces. Design tools, military standards, and expert consulting services that can be obtained from the Department of Defense and the Electromagnetic Compatibility Analysis Center (ECAC) are available to the program manager to solve any unusual EMI/EMC problem. These types of problems, if defined early enough in the program, can be mitigated by appropriate redesign.

Electric guns are a new class of weapon whose impact has not yet been experienced in a battlefield situation. In order to field-qualify these weapons, it is necessary to demonstrate that (1) the electronic components the device comprises are compatible with each other and (2) the electric gun unit viewed as a whole entity does not interfere with the operation of other electronic systems. These requirements can be met by implementing a comprehensive EMI/EMC control plan that complies with military-qualified equipment and accepted testing methods.

Military shielding standards (e.g., MIL-STD-461) generally do apply to the EMI/EMC of railguns, and established engineering design practices can be used to address these issues for an electric gun system. In the area of system integration, for example, the noise generated at ELF by the power supply to the system electronics may serve as a basis for establishing the susceptibility against the EMI/EMC produced by a railgun. Shielding the railgun so that the unwanted field falls at or below the ELF standard is one approach to satisfying EMI/EMC requirements [3, 9].

In summary, sufficient shielding can be incorporated into a practical design so that EMI/EMC problems can be overcome. This is based on observations that the fields do not appear to contain anomalous characteristics.

6.1.2 Personal Safety Issues. Present radio frequency (RF) safety guidelines are based on existing electric field standards that extend down to 1 kHz in frequency. These guidelines are based on an effects threshold of an average 4-W/kg specific absorption rate (SAR), including a tenfold safety factor, which results in an exposure limit of 0.4 W/kg. For ELF, many sweeping statements have been published but are not conclusively supported by the scientific data.

An interim conservative approach to electric field ELF exposure is suggested here, and existing guidelines will be modified as more data become available. The procedure for the interim is to:

(1) Establish an initial working limit of 1 kV/m for all electric gun systems prior to consultation with the U.S. Army Center for Health Promotion and Preventive Medicine (CHPPM),

(2) Characterize the pulsed EMI/EMC to determine the SAR dose.

(3) Assess personnel exposure using accepted techniques.

The electric fields generated by electric guns (which have a large frequency content in the ELF range) appear to pose no insurmountable concerns in the area of health hazards, and can be treated as any other EM environment for the purposes of setting standards and guidelines. Exposures are based on the time-averaged SAR such that the exposure repetition rate plays a factor in establishing guidelines; however, this process is well understood for thermal effects, so that personnel safety issues can be readily addressed once a system is identified.

It should be noted, however, that even multiple components of the EM environment can complicate published in-vitro data. A 60-Hz electric field with a 5-μT (50 mG) magnetic contaminant was needed to enhance an isolated component of the immune system (i.e., lymphocytes). A 60-Hz, pure electric or magnetic field alone was not able to produce a similar effect [54].

6.2 Technical Information From Subject Matter Experts. In order for this initial assessment to be most useful, we have discussed this study with colleagues from the Center for Electromechanics (CEM), designers and producers of compulsators. The CEM staff have estimated the fields from the busswork, the switches, and the interface to the barrel. These issues were considered in the system context. The systems-level engineering will provide detailed information necessary for finalizing the environmental shield system details.

6.3 The Shortfalls. Military systems are designed and built using informed safety standards and sound EM design and engineering principles, and these same considerations must also apply to the

development of electric armaments. Electric weapon systems that are eventually deployed will then meet the EMI/EMC, and EM radiation standards [31–33].

The EMI/EMC issues for railguns can be bounded through theoretical predictions and experimental observations of laboratory models, since with few exceptions, the results will scale to actual system dimensions [3, 49–53]. It is anticipated that EMI/EMC issues will be addressable through utilizing normal military design practices, although innovative engineering and analyses may also be required.

The situation for satisfying explicit EM effects on biological systems—in practical terms—may not be as easily accomplished as that for EMI/EMC. The reason is that the current standards are based on thermal effects, while the issues of adverse biological effects are caused by subtle low-level fields of ill-defined pulse shape and duration. Papers presented on this issue at international EMC conferences between 1991 and 1994 did not provide conclusive evidence of ***any*** adverse biological effects resulting from exposure to radio frequency fields [16–21]. Shielding levels to meet "best practice" today will result in negligible thermal heating of biological systems [16, 17].

7. How to Rectify the Shortfalls

An Electromagnetic Environment for Emerging Systems Working Group (EMEESWG) was founded by its members to provide a forum for the discussion of EM environment issues [55]. The EMEESWG provided information exchange and maintained a repository of experimental data and research not otherwise available. It is recommended that such a EMEESWG be reconstituted and continue to meet annually and be formalized by having multi-service representatives that can act as points of contact for the various ongoing electric armaments programs.

8. Conclusions

Recommendations for environment mitigation have been provided at the top level, commensurate with established guidelines [3, 7–9]. Further detailed study of the issues following are necessary at the system design level in order to optimize the balance between shielding effectiveness, overall system efficiency constraints, operational compliance, and affordability. This level of analysis and experimental validation is appropriate to undertake in depth during the engineering design phase. Such an analysis would address the following critical issues:

(1) EMI/EMC Mitigation Issues:

- Component placement
- Shielding:
  - Active
  - Passive
  - None
- Component selection:
  - Passive
  - Cost issues
- System operation:
  - Standing Operating Procedures
  - (Weapon) Firing doctrine

(2) Methods for EMI/EMC Analysis and Validation:

- Computational techniques:
  - Quasi-static, dynamic, transient, continuous
  - Component level
  - System level

- Experimental techniques:
  - Facilities
  - The Institute for Advanced Technology (IAT), U.S. Army Research Laboratory (ARL)
- Statistical studies:
  - Component level
  - Biological

The principal conclusions from this examination are:

(1) An assessment indicates that shielding is required and can be incorporated into practical armament designs so that EMI/EMC field levels can be reduced to meet those described in "best practice" guidance available today [22–27].

(2) The time rate of change of the magnetic field is the system EMI/EMC driver—even for personnel safety because the source impedance is very low in these systems [25].

(3) Shielding effectiveness as a function of system efficiency, volume, and mass trade-offs is an engineering design issue that requires design trade-off during that phase of the program [22–25, 28].

(4) Conclusive evidence that is indicative of the existence of adverse biological effects on humans (both thermal and nonthermal) resulting from exposure to pulsed EM fields does not exist. Should such counterevidence emerge in the future, it is important to note that the process of establishing guidelines for personnel safety is well understood and can be readily addressed once a system and its effects are defined [4–21].

(5) Shielding for a monopulse field source may give rise to guided surface waves requiring further damping, which is recommended for further study to identify the most effective efficient techniques of meeting "best practice" field levels.

9. References

1. Pratap, S., and M. Driga. "Compensation in Pulsed Alternators." *IEEE Transactions on Magnetics*, vol. 35, no. 1, January 1999.

2. Mongeau, P., C. Gunsallus, R. Pasquale, K. Plant, and M. Piercey. "High-Performance Disk Alternators." *IEEE Transactions of Magnetics*, vol. 25, no. 1, January 1989.

3. Haberman, M. L. "EMI/EMC Issues Associated With Railguns." ECAC-CR-93-086, DOD Electromagnetic Compatibility Analysis Center.

4. Cartwright, C. E., P. N. Breyesse, and L. Booher. "Magnetic Field Exposures in a Petroleum Refinery." *Appl. Occup. Environ.*, vol. HYG 8, no. 6, pp. 587–591, 1993.

5. Deadman, J. E., M. Camus, B. G. Armstrong, P. Heroux, et al. "Occupational and Residential 60-Hz Electromagnetic Fields and High-Frequency Electric Transients: Exposure Assessment Using a New Dosimeter." *Journal of the American Industrial Hygiene Association*, vol. 49, no. 8, pp. 409–418, 1988.

6. Breysse, P. N., G. M. Matanoski, E. A. Elliott, M. Francis, W. Kaune, and K. Thomas. "60-Hz Magnetic Field Exposure Assessment for an Investigation of Leukemia in Telephone Workers." *American Journal of Industrial Medicine*, vol. 26, pp. 681–691, 1994.

7. The Institute of Electrical and Electronics Engineers. "Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz." IEEE SCC28, 1991, IEEE Standards Coordinating Committee SCC 28 on Non-Ionizing Radiation Hazards, NY, November 1992.

8. Jammet, H. P., et al. "Interim Guidelines on Limits of Exposure to 50/60-Hz Electric and Magnetic Fields." *Health Physics*, vol. 58, pp. 113–122, 1990.

9. Office of the Surgeon General. "The Sub-Radio Frequency Spectrum (Static to 3 kHz Band)." Memorandum SGPS-PSP-O, 3 January 1994.

10. Wachtel, H., et al. "Comparison of the Efficacy of Pulsed Versus CW RF in Evoking Reflexive Movements in Mice." *Proceedings of the 11th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, November 1989.

11. Chou, C. K., H. Bassen, J. Osepchuk, G. Balzano, R. Petersen, M. Meitz, R. Cleveland, J. C. Lin, and L. Heynick. "Radio Frequency Electromagnetic Exposure." *Journal of Bioelectromagnetics*, vol. 17, pp. 195–208, 1996.

12. Foster, K. R., L. S. Erdreich, and J.E. Moulder. "Weak Electromagnetic Fields and Cancer in the Context of Risk Assessment." *Proceedings of the IEEE*, vol. 85, no. 5, pp. 733–751, May 1997.

13. Tenforde, T. S. "Assessment of Environmental Impacts and Human Health Effects of Magnetic Fields From Superconducting Magnetic Energy Storage Engineering Test Model." Prepared as Appendix B of the Environmental Impact Assessment for the SMES project for the U.S. Army Corps of Engineers.

14. IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz, EE C-95.1, 1991.

15. Geneva International Labour Office. "Protection of Workers From Power Frequency Electric and Magnetic Fields." Prepared by the International Non-ionizing Radiation of the International Radiation Protection Association in collaboration with the International Labour Organization, 1993.

16. Stuckly, M. A. "Health Effects of Electromagnetic Fields: Progressed and New Directions." *Proceedings of the 9th International Zurich Symposium and Technical Exhibition on Electromagnetic Compatibility*, Zurich, Switzerland, 12–14 March 1991.

17. Anderson, T. E. "Biological Effects of Electromagnetic Fields." *Proceedings of the 9th International Zurich Symposium and Technical Exhibition on Electromagnetic Compatibility*, Zurich, Switzerland, 12–14 March 1991.

18. Hoeft, L. O. "Models for the Effects of Electromagnetic Fields on the Occurrence of Cancer." *Proceedings of the 12th International Wroclaw Symposium and Exhibition on Electromagnetic Compatibility*, Wroclaw, Poland, 2–4 September 1992.

19. Szmigielski, S. "Cancer and Electromagnetic Field." *Proceedings of the 12th International Wroclaw Symposium and Exhibition on Electromagnetic Compatibility*, Wroclaw, Poland, 2–4 September 1992.

20. Miro, L. "Biological Effects of Electromagnetic Fields." *Proceedings of the 12th International Wroclaw Symposium and Exhibition on Electromagnetic Compatibility*, Wroclaw, Poland, 28 June–1 July 1994.

21. National Research Council. *Possible Health Effects of Exposure to Residential Electric and Magnetic Fields*, Washington, DC: National Academy Press, 1997.

22. Terman, F. E. *Radio Engineers' Handbook*. New York, NY: McGraw-Hill Book Company, Inc., pp. 131–134, 1943.

23. Ellwood, W. B. "Magnetic Shields." *Bell Lab. Rec.*, vol. 17, p. 93, November 1938.

24. Gustafson, W. G. "Magnetic Shielding of Transformers at Audio Frequencies." *Bell System Technical Journal*, vol. 17, p. 416, July 1938.

25. Bumby, J. R. *Superconducting Rotating Electrical Machines.* Department of Electrical Engineering, University of Durham, Oxford: Clarendon Press, 1983.

26. Zielinski, A. E. "In-Bore Magnetic Field Management." ARL-TR-1914, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, April 1999.

27. Zielinski, A., I. Kohlberg, J. Bennett, C. Le, and W. J. Sarjeant. "Shielding Considerations for Transient Magnetic Fields Produced by A Pulsed Moving Conductor System." Presented at the 3rd International All Electric Combat Vehicle Conference, Germany, September 1999.

28. Chirlian, P. M. *Basic Network Theory.* New York, NY: McGraw-Hill Book Company, Inc., pp. 375–377, 1969.

29. Hitchcock, R. T., and R. M. Patterson. *Radio-Frequency and ELF Electromagnetic Energies: A Handbook for Health Professionals.* American Conference of Governmental Industrial Hygienist (ACGIH) Publication 9525, 1995.

30. Pratap, S. "Transient Eddy Current Distribution in the Shield of the Passively Compensated Compulsator-Air-Core Machines." *IEEE Transactions on Magnetics*, vol. 27, no. 4, pp. 3710–3720, July 1991.

31. Early, M. J. "Transient Testing According to the EMC Directive." *1997 Interference Technology Engineer's Master, Directory and Design Guide for the Control of EMI&E*, published by the International Journal of EMC, pp. 44–47, 50–52, 1997.

32. Hopkins, M. "An Overview of the EMC Directive." *1997 Interference Technology Engineer's Master, Directory and Design Guide for the Control of EMI&E*, published by the International Journal of EMC, pp. 66–70, 1997.

33. "Government Moves E^3 Leadership to DOD Level." *Progress in EMC*, published by R&B Enterprises, West Conshohocken, PA.

34. Pratap, S. B. "Environmental Shielding of FTP Class Generators." White Paper PL-280, The University of Texas at Austin, Austin, TX, 5 February 1997.

35. Le, C., and A. Zielinski. "Preliminary Findings on Magnetic Shielding Effectiveness for Electromagnetic Railgun Applications." *Proceedings of the 6th European Symposium on Electromagnetic Launch*, May 1997.

36. Marinos, C. "Flexible Coaxial Cables for EM and ETC Gun Systems." US Patent 5,656,796, August 1997.

37. Zielinski, A. E., C. Le, J. Bennett, and I. Kohlberg. "Railgun Electric Fields: Theory And Experiment." *IEEE Transactions of Magnetics*, vol. 31, no. 1, January 1999.

38. Freilikher, V. D., Yu. V. Tarasov, and B. Liansky. "Propagation of Pulse in Randomly Layered Media." *Progress in Electromagnetics Research Symposium*, Huis ter Duin, Noordwijk, The Netherlands, 11–15 July 1994.

39. Glatz, J. "Application of Composite Materials to Electronic Enclosures." *1997 Interference Technology Engineer's Master, Directory and Design Guide for the Control of EMI&E*, published by the International Journal of EMC, pp. 40–42, 264–268, 1997.

40. Advance Magnetics, Inc. "Magnetic Shields of Permalloy Alloys Show Operation to B_{sat} Greater Than 0.7 T."

41. Coburn, W., C. Reiff, L. Albright, and A. Mauroni. "Shielding Effectiveness Test Report for a TI-Shield Enclosure." ARL Report, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1995.

42. Electromagnetic Pulse Radiation Environment Simulator for Ships (EMPRESS II). "Final Environmental Impact Statement for the Proposed Operation of the Navy Electromagnetic Pulse Radiation Environment Simulator for Ships (EMPRESS II) in the Chesapeake Bay and Atlantic Ocean." The Supplemental Draft Environment Impact Statement (SDEIS) prepared for the Defense Nuclear Agency, April 1988.

43. Guttman, J. "Investigation of Potential Association Between Wiring Configuration Codes and Magnetic Field Transient Events." Electric and Magnetic Field Abstracts, 1992 Annual Report, EPRI TR-102928, August 1993.

44. Guttman, J. L., J. C. Nipple, and J. M. Silva. "Transient Data Acquisition System Used in the California Pilot Study: A Series of 24-Hour Measurements of Transient Magnetic Fields Performed in 21 Residences." Annual Review of Research on Biological Effects of Electric and Magnetic Fields from the Generation, Delivery, and Use of Electricity, U.S. Dept. of Energy, GA, pp. 57–58, 1993.

45. Delgado, J. M., R. J. Leal, J. L. Monteagudo, and M. G. Garcia. "Embryological Changes Induced by Weak, Extremely Low Frequency Electromagnetic Fields." *J. Anat.*, vol. 134, no. 3, pp. 533–551, 1982.

46. Delgado, J. M. "Biological Effects of Extremely Low Frequency Electromagnetic Fields." *J. Bioelectr*, vol. 4, no. 1, pp. 75–91, 1985.

47. Bersani, F., C. Franceschi, D. Monti, A. Cossarizza, R. Cadossi, M. R. Scarfi, G. Castellani, P. Conti, M. Reale, and G. E. Gigante. "Lymphocyte Proliferation After Exposure to Two Different Kinds of Pulsed Magnetic Fields: Intercomparison Between Two Different Labs (Meeting Abstract)." First World Conference for Electricity and Magnetism in Biology and Medicine, FL, p. 58, June 1992.

48. Reiter, R. J., B. Poeggeler, L. D. Chen, D. X. Tan, M. Abe, M. Hara, P. Orhii, and L. Barlow-Walden. "Regulation of Pineal Melatonin Synthesis by Magnetic Field Exposure: Implications for Cancer (Meeting Abstract)." Bioelectromagentics Society, 16th Annual Meeting, Denmark, p. 99, June 1994.

49. Kohlberg, I., and W. O. Coburn. "A Solution for the Three-Dimensional Railgun Current Distribution and Electromagnetic Fields of a Rail Launcher." *IEEE Trans. On Magnetics*, vol. 30, no.1, January 1995.

50. Coburn, W. O., C. Le, D. DeTroye, G. Blair, and W. Williams. "Electromagnetic Field Measurements Near a Railgun." *IEEE Trans. On Magnetics*, vol. 30, no.1, January 1995.

51. Coburn,W. O., and W. Williams. "Static and Quasi-static Models for the Magnetic Field of a Railgun." *IEEE Trans. On Magnetcis*, vol. 30, no. 1, January 1995.

52. Coburn, W. O., I. Kohlberg, and W. Williams. "Environment and Circuit Model for Capacitor Based Railguns." *Proceedings of the EUROEM 94 International Symposium,* Bordeaux, France, June 1994.

53. Kohlberg, I., and W. O. Coburn. "Theoretical and Experimental Investigation of Electromagnetic Fields Generated By Railgun." *Proceedings of the 12th International Wroclaw Symposium and Exhibition on Electromagnetic Compatibility*, Wroclaw, Poland, 28 June–1 July 1994.

54. Morris, J. E., and B. J. McClanahan. "In-Vitro Exposure of Lymphocytes to 60-Hz Electric and Magnetic Fields (Meeting Abstract)." Bioelectromagnetics Society, 8th Annual Meeting, WI, p. 64, June 1986.

55. "Management Synopsis-Third Meeting of the Electromagnetic Environments for Emerging Systems Working Group (EMEESWG)." ARDEC Memo Report, U.S. Army Armament Research, Development, and Engineering Center, Picatinny Arsenal, NJ, 28 August 1993.

INTENTIONALLY LEFT BLANK.

Appendix:

Summary of Select Supportive Literature

INTENTIONALLY LEFT BLANK.

1. Single-Pulse, High-Frequency Systems [1–4]

Finding: Single-shot nonionizing radiation pulse contains mainly harmonics well above 1 MHz, and hence is not directly applicable to this present study.

There are several references noted that are relevant to the electromagnetic interference (EMI) considerations in the electromaagnetic compatibility (ECM) case. The environmental impact statement analyses for this pulsed, high-energy system is described in reference 4. The major interest is in the approach taken to address concerns with operation of such a very large, unshielded, near-free-field radiation system. An additional reference addresses the circa 1991 recommendations for field management for electrical safety considerations to humans [1]. A final reference relates continuous-wave (CW) fields to pulsed fields in terms of actual behavioral impact [2].

2. CW Radio Frequency (RF) Shielding for Ultra-Lightweight Systems [5, 6]

Finding: This report addresses 100 MHz to several GHz shielding for very lightweight applications [5, 6]. In Figure 4, p. 266 of reference 5, a summary is presented to the relative shielding effectiveness of diverse electromagnetic (EM) flat panel shielding architectures. Note that monopulse impulse shielding effectiveness is **not** addressed in these RF measurements and must be considered for unipolar impulse conditions such as for the ECM power conditioning system between the switch output and the gun barrel.

3. Transient Burst Immunity of Industrial Power Electronics in the Millisecond Class Pulse Regime [7]

Finding: IEC 801-4/1000-4-4 for transient burst immunity and IEC 801-5/1000-4-5 for lightning have been written to address the EMC of industrial process measurement and control equipment. The pulse waveform utilized is millisecond burst duration, comparable to the ECM regime of operation. In this report, repetitive issues are addressed for bursts up to 5 kHz and voltages to 2 kV [7].

The energies are not comparable to electric armaments operation, so that saturation effects may need to be considered. This methodology of measurement could be directly applied to the further consideration of tests in the electric armaments systems.

4. International Considerations for EMI/EMC [8]

Finding: In this report, the directive applies to essentially all electronic products shipped into the European Union beginning 1 January 1996 [8]. The directive appears to cover **all** commercial and military electronics.

Because of the restrictive EM signatures permitted, further clarification is recommended as the electric armament program progresses to avoid any export constraints on our military electronics.

5. Joint Spectrum Center [9]

Finding: The highest ranking E^3 Organization established at the Department of Defense level is located at the Joint Spectrum Center (formally the ECAC) in Annapolis, MD. The primary function of the organization is to lead the E^3 Training Program, the E^3 Standardization Program, and other E^3 activities [9].

Recent activities have been disseminating the essence of Military Standard (MIL-STD)-464 and the ongoing harmonization of commercial/military E^3 standards. Note that these standards all appear to address relatively low magnetic field levels compared to the prime fields from the compulsator.

Estimates in this study show that appropriate magnetic multilevel shielding is expected to reduce far fields to levels significantly less than recommended practice levels. Thus, measurement techniques in current military standards should suffice for shielding effectiveness validation. Electric field shielding does not appear to be an issue.

6. Biological Power Absorption Definitions and Energy Implications [3]

Finding: The Specific Absorption Rate (SAR) is formally defined as the time derivative of the incremental energy absorbed by (dissipated in) an incremental mass contained in a volume of a given density. SAR also applies to magnetic absorption as well [3].

In general, transient effects are not included. Rather a continuous wave of RF power is incident upon a given test specimen. This is the reason peak field limits—either magnetic or electric—are constrained to be below the recommended practice for RF continuous fields.

Note carefully that there does not appear to be strong experimental or theoretical foundations for such an approach, especially when considering unipolar single or burst train pulses in an operational system [3]. The biological effects considered are thermal heating as described in detail in the work [3].

7. Results of Large-Scale Biological EMI Effects From 50/60-Hz Power Line Fields [10, 11]

Finding: Results of hundreds of experiments on in vitro and in vivo studies involving low frequencies—mainly 50/60 Hz power line—show that low-frequency magnetic fields are not genotoxic [10, 11].

At suggested maximum magnetic field body levels—of less than 1 μT—the induced electric fields in the body are orders of magnitude smaller than fields that naturally occur due to natural bioelectric phenomena [10].

The whole body exposure limit is 0.4 W/kg for continuous RF power incident on the entire body. This is the recommended practice level for continuous wave sources and alternating current (AC) signals. When large pulsed-power-generating devices become operational, this level must be translated into applicable field levels for the systems of interest.

8. Management Synopsis – Third Meeting of the Electromagnetic Environment for Emerging Systems Working Group (EMEESWG) (Currently Inactive) [12]

Finding: The EMEESWG was first formed on 7 April 1993. Present at this first meeting were representatives from the U.S. Army Research Laboratory (ARL), the U.S. Army Armament Research, Development, and Engineering Center (ARDEC), and the Electromagnetic Compatibility Analysis Center (ECAC). All were in agreement that the most efficient and cost effective way to characterize the environment was to combine resources from the various programs. These resources would include, but not be limited to, data exchange, modeling, manpower, and data repository. Also, it was the consensus to expand participation to all government services, government agencies, private sectors, and universities interested in this area.

The second meeting was held at ECAC, Annapolis, MD, 8–10 October 1993. Representatives from the Armed Services, government contractors, and universities attended this meeting. It was decided to meet once a year before the end of the fiscal year.

Technical agreements between the Closed Combat Armaments Center, ARDEC, and ARL Weapons Technology Directorate (now the Weapons and Materials Research Directorate) were formalized in the way of a Technology Program Annex Addendum, which is a document agreeing to support on-going efforts between the two organizations. Also, a memorandum of understanding (MOU) between ARL Weapons Technology Directorate and ECAC was established. ECAC was designated as the data repository site for all data pertaining to the EMEESWG.

Computational models (static and quasistatic) to predict the magnetic fields generated by small- and medium-caliber railguns were completed. EM field measurements were conducted near those systems. The electric field and magnetic field measurements were designed to characterize the transient EM environment external to these particular gun systems. The experimental data helped verify the results obtained from the computational models, and it was concluded that the models provide an engineering tool for transient EM environment prediction.

9. Prismatic Shielding of Power Electronics [13–15]

Finding: TI-Shield from Texas Instruments, Inc., was evaluated in comparison to pure copper shielding under actual EM gun, millisecond duration, conditions. Recent tests [14] indicate that this material is quite effective in magnetic fields up to tens of milliteslas [14].

TI-Shield is constructed from 0.09-mm copper foil, bonded to 0.2-mm Permalloy 49 and then 0.08-mm copper foil. These experiments showed quite promising potential of TI-Shield in the shielding of the lower frequency magnetic fields from EM railguns.

Further research at scale fields is necessary to evaluate any saturation effects in the shield composite [15]. If this material is utilized as secondary shielding at B_{max} of a few milliteslas, well below Permalloy saturation, attenuations within a few decibels of those measured would be expected [13].

For shielding at frequencies 150 kHz to 850 MHz, TI-Shield at low-signal levels was shown to exceed the requirements of MIL-STD-907B, testing in accordance with MIL-STD-285 (superseded by IEEE Std. 299-1991).

The material is quite cost effective, lightweight, and can be readily installed using standard mechanical workmanship techniques.

This readily available shielding material would be a strong candidate for spot shielding in EM weapon systems at locations where high-frequency burst pulses may present themselves. One example of this could be in screening recovery switch noise that is sometimes observed during turn-off of high action switches, and has been observed in thyratrons as well as medium power thyristors. Normally, snubber networks are utilized to dampen such oscillations; however, in these larger energy systems, snubber-free or snubber-minimum designs will increase efficiency and reduce volume of the system, a desirable attribute [15].

10. Environmental Impact Statement [16]

Finding: The study is an excellent approach to use for developing any environmental impact statements regarding any fieldable EM weapons system [16]. This report is only available from the U.S. Army Corps of Engineers:

U.S. Army Engineer District, Mobile
ATTN: PD-EI (Mike Eubanks)
P.O. Box 2288
Mobile, AL 36628-0001
(205) 694-3861

References

1. The Institute of Electrical and Electronics Engineers. "Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz." IEEE SCC28, 1991, IEEE Standards Coordinating Committee SCC 28 on Non-Ionizing Radiation Hazards, NY, November 1992.

2. Jammet, H. P., et al. "Interim Guidelines on Limits of Exposure to 50/60-Hz Electric and Magnetic Fields." *Health Physics*, vol. 58, pp. 113–122, 1990.

3. Chou, C. K., H. Bassen, J. Osepchuk, G. Balzano, R. Petersen, M. Meitz, R. Cleveland, J. C. Lin, and L. Heynick. "Radio Frequency Electromagnetic Exposure." *Journal of Bioelectromagnetics*, vol. 17, pp. 195–208, 1996.

4. Electromagnetic Pulse Radiation Environment Simulator for Ships (EMPRESS II). "Final Environmental Impact Statement for the Proposed Operation of the Navy Electromagnetic Pulse Radiation Environment Simulator for Ships (EMPRESS II) in the Chesapeake Bay and Atlantic Ocean." The Supplemental Draft Environment Impact Statement (SDEIS) prepared for the Defense Nuclear Agency, April 1988.

5. Glatz, J. "Application of Composite Materials to Electronic Enclosures." *1997 Interference Technology Engineer's Master, Directory and Design Guide for the Control of EMI&E*, published by the International Journal of EMC, pp. 40–42, 264–268, 1997.

6. Advance Magnetics, Inc. "Magnetic Shields of Permalloy Alloys Show Operation to B_{sat} Greater Than 0.7 T."

7. Early, M. J. "Transient Testing According to the EMC Directive." *1997 Interference Technology Engineer's Master, Directory and Design Guide for the Control of EMI&E*, published by the International Journal of EMC, pp. 44–47, 50–52, 1997.

8. Hopkins, M. "An Overview of the EMC Directive." *1997 Interference Technology Engineer's Master, Directory and Design Guide for the Control of EMI&E*, published by the International Journal of EMC, pp. 66–70, 1997.

9. "Government Moves E^3 Leadership to DOD Level." *Progress in EMC*, published by R&B Enterprises, West Conshohocken, PA.

10. Foster, K. R., L. S. Erdreich, and J.E. Moulder. "Weak Electromagnetic Fields and Cancer in the Context of Risk Assessment." *Proceedings of the IEEE*, vol. 85, no. 5, pp. 733–751, May 1997.

11. National Research Council. *Possible Health Effects of Exposure to Residential Electric and Magnetic Fields*, Washington, DC: National Academy Press, 1997.

12. "Management Synopsis-Third Meeting of the Electromagnetic Environments for Emerging Systems Working Group (EMEESWG)." ARDEC Memo Report, U.S. Army Armament Research, Development, and Engineering Center, Picatinny Arsenal, NJ, 28 August 1993.

13. Terman, F. E. *Radio Engineers' Handbook.* New York, NY: McGraw-Hill Book Company, Inc., pp. 131–134, 1943.

14. Zielinski, A. E. "In-Bore Magnetic Field Management." ARL-TR-1914, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, April 1999.

15. Coburn, W., C. Reiff, L. Albright, and A. Mauroni. "Shielding Effectiveness Test Report for a TI-Shield Enclosure." ARL Report, U.S. Army Research Laboratory, Aberdeen Proving Ground, MD, 1995.

16. Tenforde, T. S. "Assessment of Environmental Impacts and Human Health Effects of Magnetic Fields From Superconducting Magnetic Energy Storage Engineering Test Model." Prepared as Appendix B of the Environmental Impact Assessment for the SMES project for the U.S. Army Corps of Engineers.

NO. OF COPIES	ORGANIZATION
2	DEFENSE TECHNICAL INFORMATION CENTER DTIC DDA 8725 JOHN J KINGMAN RD STE 0944 FT BELVOIR VA 22060-6218
1	HQDA DAMO FDT 400 ARMY PENTAGON WASHINGTON DC 20310-0460
1	OSD OUSD(A&T)/ODDDR&E(R) R J TREW THE PENTAGON WASHINGTON DC 20301-7100
1	DPTY CG FOR RDA US ARMY MATERIEL CMD AMCRDA 5001 EISENHOWER AVE ALEXANDRIA VA 22333-0001
1	INST FOR ADVNCD TCHNLGY THE UNIV OF TEXAS AT AUSTIN PO BOX 202797 AUSTIN TX 78720-2797
1	DARPA B KASPAR 3701 N FAIRFAX DR ARLINGTON VA 22203-1714
1	NAVAL SURFACE WARFARE CTR CODE B07 J PENNELLA 17320 DAHLGREN RD BLDG 1470 RM 1101 DAHLGREN VA 22448-5100
1	US MILITARY ACADEMY MATH SCI CTR OF EXCELLENCE DEPT OF MATHEMATICAL SCI MADN MATH THAYER HALL WEST POINT NY 10996-1786

NO. OF COPIES	ORGANIZATION
1	DIRECTOR US ARMY RESEARCH LAB AMSRL D D R SMITH 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRL DD 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB AMSRL CS AS (RECORDS MGMT) 2800 POWDER MILL RD ADELPHI MD 20783-1145
3	DIRECTOR US ARMY RESEARCH LAB AMSRL CI LL 2800 POWDER MILL RD ADELPHI MD 20783-1145
	ABERDEEN PROVING GROUND
4	DIR USARL AMSRL CI LP (BLDG 305)

NO. OF COPIES	ORGANIZATION
1	DIRECTOR USARL AMSRL CP CA D SNIDER 2800 POWDER MILL RD ADELPHI MD 20783
1	COMMANDER US ARMY ARDEC AMSTA AR FSE T GORA PICATINNY ARSENAL NJ 07806-5000
3	COMMANDER US ARMY ARDEC AMSTA AR TD PICATINNY ARSENAL NJ 07806-5000
5	COMMANDER US ARMY TACOM AMSTA JSK S GOODMAN J FLORENCE AMSTA TR D B RAJU L HINOJOSA D OSTBERG WARREN MI 48397-5000
5	PM SADARM SFAE GCSS SD COL B ELLIS M DEVINE W MEASSI J PRITCHARD S HROWNAK PICATINNY ARSENAL NJ 07806-5000
4	COMMANDER US ARMY ARDEC AMSTA AR CCH S MUSALLI R CARR M LUCIANO T LOUCEIRO PICATINNY ARSENAL NJ 07806-5000

NO. OF COPIES	ORGANIZATION
1	COMMANDER US ARMY ARDEC F MCLAUGHLIN PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR E FENNEL (2 CPS) PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR CCH P J LUTZ PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR FSF T C LIVECCHIA PICATINNY ARSENAL NJ 07806-5000
1	COMMANDER US ARMY ARDEC AMSTA AR QAC T C C PATEL PICATINNY ARSENAL NJ 07806-5000
2	COMMANDER US ARMY ARDEC AMSTA AR M D DEMILLA F DIORIO PICATINNY ARSENAL NJ 07806-5000
1	DIR FOR THE DIRECTORATE OF FORCE DEVELOPMENT US ARMY ARMOR CENTER COL E BRYLA FT KNOX KY 40121-5000

NO. OF COPIES	ORGANIZATION
1	COMMANDER US ARMY MATERIAL CMD AMC DCG T C KITCHENS 5001 EISENHOWER BLVD ALEXANDRIA VA 22333-0001
2	DIRECTOR US ARMY RESARCH LAB C LE G MCNALLY 2800 POWDER MILL RD ADELPHI MD 20783-1145
1	OFC OF THE DIRECTOR DEFENSE RSCH & ENGRG C KITCHENS 3080 DEFENSE PENTAGON WASHINGTON DC 20301-3080
1	COMMANDER US ARMY MISSILE COMMAND AMSMI RD DR MCCORKLE REDSTONE ARSENAL AL 35898-5240
2	US ARMY TACOM ARDEC J CHAPIN M TOURNER AMSTA TR D MS 207 WARREN MI 48397-5000
1	US ARMY TACOM ARDEC J BENNETT FSAE GCSS TMA BLDG 354 PICATINNY ARSENAL NJ 07806-5000
3	INST FOR ADVANCED TECH UNIV OF TEXAS AT AUSTIN P SULLIVAN F STEPHANI I MCNAB 4030 2 WEST BRAKER LANE AUSTIN TX 78759-5329

NO. OF COPIES	ORGANIZATION
4	UNIV OF TEXAS AT AUSTIN CENTER FOR ELECT A WALLS J KITZMILLER S PRATAP PRC MAIL CODE R7000 AUSTIN TX 78712
1	LOCKHEED MARTIN VOUGHT R TAYLOR PO BOX 650003 MS WT 21 DALLAS TX 75265-0003
1	INST FOR DEFENSE ANALYSIS I KOHLBERG 1801 N BEAUREGARD ST ALEXANDRIA VA 22311
1	UNITED DEFENSE BOB MARINOS 1205 COLEMAN AVE SANTA CLARA CA 95050
5	UNIV AT BUFFALO SUNY AB J SARJEANT PO BOX 601900 BUFFALO NY 14260-1900
2	UDLP B GOODELL R JOHNSON MS M170 4800 EAST RIVER RD MINNEAPOLIS MN 55421-1498
1	UNIV OF TEXAS AT AUSTIN M DRIGA DEPT OF ECE MAIL CODE C0803 AUSTIN TX 78712
1	SAIC G CHRYSSOMALLIS 3800 WEST 80TH ST STE 1090 BLOOMINGTON MN 55431

NO. OF COPIES	ORGANIZATION
1	SAIC J BATTEH 1225 JOHNSON FERRY RD STE 100 MARIETTA GA 30068
1	SAIC K A JAMISON 1247 B N EGLIN PKWY SHALIMAR FL 32579
2	IAP RESEARCH INC D BAUER J BARBER 2763 CULVER AVE DAYTON OH 45429-3723
2	MAXWELL TECHNOLOGIES P REIDY T WOLFE 9244 BALBOA AVENUE SAN DIEGO CA 92123
1	NORTH CAROLINA STATE UNIV M BOURHAM DEPT OF NUCLEAR ENGR BOX 7909 RALEIGH NC 27695-7909
1	MAXWELL PHYSICS INTERNATIONAL C GILMAN 2700 MERCED STREET PO BOX 5010 SAN LEANDRO CA 94577-0599
1	ATA ASSOCIATES W ISBELL PO BOX 6570 SANTA BARBARA CA 93160-6570
1	PHILLIPS LABORATORY WSR C BAUM KIRTLAND AFB NM 87117

NO. OF COPIES	ORGANIZATION
1	CENTER FOR NAVAL ANALYSIS F BOMSE 4401 FORD AVENUE PO BOX 16268 ALEXANDRIA VA 22302-0268
1	SPECTRAL SYNTHESIS LABS R GARDNER 6152 MANCHESTER PARK CIR ALEXANDRIA VA 22310-4957
1	DEPUTY DIRECTOR TECHNLGY IDENTIFICATION & ANALYSIS CENTER G BOEZER SCIENCE & TECHNLGY DIV INSTITUTE FOR DEFENSE ANALYSES 1801 N BEAUREGARD ST ALEXANDRIA VA 22311-1772
1	BDM INTERNATIONAL INC ADVISOR TO THE PRESIDENT & CEO J BRADDOCK SENIOR FELLOW FOR TECHNLGY & PUBLIC POLICY 1501 BDM WAY MCLEAN VA 22102-3204
1	SANDIA NATL LABORATORIES M BUTTRAM MS 1153 PO BOX 5800 ALBUQUERQUE NM 87185-1153
1	CORPORATE STAFF DYNETICS INC R CLINTON 1000 EXPLORER BLVD PO BOX 5500 HUNTSVILLE AL 35806

NO. OF COPIES	ORGANIZATION
1	DIRECTOR MATLS SCIENCE DIVISION ARMY RESEARCH OFFICE A CROWSON PO BOX 12211 RESEARCH TRIANGLE PARK NC 27709
1	NAVAL AIR ENGRG CTR CHIEF ENGINEER G DI BIASE CODE 4.8 ENGINEERING AND PRODUCT SUPPORT DIRECTORATE LAKEHURST NJ 08733
1	AIR FORCE RSCH LAB DEPUTY CHIEF WPNS SECTOR PLANS & PRGMS DIR LTC J GODSEY AFRL XPW 1864 4TH ST STE 1 WRIGHT PATTERSON AFB OH 45433-7131

NO. OF COPIES	ORGANIZATION
	ABERDEEN PROVING GROUND
	DIR USARL AMSRL WM I MAY L JOHNSON AMSRL B A HORST E SCHMIDT A TANNER AMSRL WM WD J POWELL AMSRL WM B G WREN B FORCH W DAMICO AMSRL WM BC P PLOSTINS D LYON J GARNER V OSKAY M BUNDY J SAHU P WEINACHT H EDGE B GUIDOS A ZIELINSKI D WEBB G COOPER K SOENCKSEN S WILKERSON T ERLINE J NEWILL

INTENTIONALLY LEFT BLANK.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project(0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	May 2000	Final, Sep 98–Sep 99

4. TITLE AND SUBTITLE

An Examination of the Nature, Effects, and Control of Electromagnetic Fields

5. FUNDING NUMBERS

1L1622618.H80

6. AUTHOR(S)

W. J. Sargeant, C. Marinos, and A. Zielinski

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
ATTN: AMSRL-WM-BC
Aberdeen Proving Ground, MD 21005-5066

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-2232

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

10.SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Electromagnetic (EM) armaments and electric launchers are emerging systems that are of increasing importance to the armed forces. Included in this category are the railgun, coilgun, reconnection gun, electrothermal (ET) gun, and electrothermal-chemical (ETC) gun. The system design issues for managing EM fields generated by these devices and their associated pulsed power systems, which may include compulsators and pulse disk alternators, in the military applications for which they are intended have been the subject of this study.

14. SUBJECT TERMS	15. NUMBER OF PAGES
electromagnetic fields, environment, exposure	45
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. ARL Report Number/Author ARL-TR-2232 (Sargeant) ________ Date of Report May 2000 ________

2. Date Report Received ________________________________

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ________________________________

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ________________________________

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ________________________________

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ________________________________

CURRENT ADDRESS

____
Organization

____
Name E-mail Name

____
Street or P.O. Box No.

____
City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the Current or Correct address above and the Old or Incorrect address below.

OLD ADDRESS

____
Organization

____
Name

____
Street or P.O. Box No.

____
City, State, Zip Code

(Remove this sheet, fold as indicated, tape closed, and mail.)

(DO NOT STAPLE)